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Achieving thermal comfort in naturally ventilated rammed earth houses

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ABSTRACT

Rammed earth buildings are normally perceived to have desirable thermal performance due to the thermal mass effect of the walls; however, this can only be achieved when other design strategies are taken into account such as insulation, double glazing, shading and ventilation. This paper reports on a study of the impact of using rammed earth walls on the indoor temperatures in a non-heated or cooled hypothetical house by using a thermal simulation program. The predicted indoor operative temperatures are compared to the acceptable operative indoor temperatures based on the Adaptive Comfort Standard in ASHRAE 55-20113. The building was considered in three Australian climate zones (zones 3, 5 and 7) representing hot arid, warm temperate and cool temperate climates, respectively.

The effect of four design parameters on the indoor temperatures of this hypothetical uninsulated rammed earth wall house was evaluated, including the influence of window size, shading, ventilation rate and wall thickness. It was found that a house constructed of uninsulated rammed earth with a typical wall thickness of 300 mm in climate zones 3, 5 and 7 can only achieve indoor operative temperatures that are within the 80% acceptability limits based on the adaptive model for 77%, 68% and 45% of the time, respectively, if the window size, shading and ventilation rate are optimised. With a 30 mm thick layer of polystyrene insulation inserted into the middle of the rammed earth walls, these performance values can be further increased to 89%, 90% and 58% respectively.

1. Introduction

In recent years there has been a revival of interest in rammed earth (RE) construction. RE is perceived to be environmental friendly and sustainable as it is a construction material with extremely low embodied energy, in particular when locally available material is used [1–4]. Using material that is available locally means considerably reducing the energy consumed for manufacturing and transporting, which accounts for 29%–40% of the total embodied energy of that material [5,6]. In addition, rammed earth houses are claimed to be thermally efficient because they are able to maintain a reasonably comfortable indoor temperatures year around without much input of external energy for heating and cooling [7]. This is because rammed earth constructions are characteristically built with thick earthen walls for stability (typically 300 mm–600 mm thick [8]), and the thermal mass of these thick walls can delay the transmission of heat from the outside to the inside due to the wall's long time lag in hot summer days (typical 300 mm thick rammed earth walls can provide a thermal time lag of about 10 h [9,10]), meaning that the maximum indoor temperature will occur much later after the outdoor temperature peaks during the day and thus cool night-time ventilation can be used to reduce the indoor temperature [11]. In cold winter days, the thermal mass stores much of the heat it absorbs during daytime and the stored heat will be released to the inside of the house at night and help to warm the spaces [11,12].

However, according to a survey conducted by Paul and Taylor [13], rammed earth buildings do not necessarily provide better thermal performance than conventional buildings. The occupants claimed that the internal environment of the rammed earth buildings was warm in summer, leading to a low level of satisfaction. Another study by Taylor et al. [14] reported that a naturally ventilated rammed earth office building (with hydronic heating and cooling) could not provide adequate thermal comfort in both winter and summer or expected energy saving, unless the external walls were insulated. Rammed earth walls alone cannot guarantee thermal comfort or energy conservation and the building

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performance generally improves when other design strategies, such as insulation [14], glazing, shading and ventilation [15], are implemented. Inappropriate use of thermal mass may in fact cause negative impacts on thermal comfort, hence it is recommended that the integration of thermal mass and other design parameters be optimised and this optimisation be conducted using thermal performance software tools [16]. The study presented in this paper investigated the effects of key design parameters on the thermal comfort of naturally ventilated rammed earth houses (i.e. no heating or cooling), in order to identify the optimum value of each design parameter corresponding to the maximum thermal performance and provide recommendations for more informed designs of rammed earth houses.

2. Thermal performance measure for naturally ventilated buildings

The main focus of the present study is the effect of key design parameters on the thermal performance of a hypothetical rammed earth house without heating and cooling. In naturally ventilated houses, thermal performance mainly refers to the internal thermal comfort as opposed to energy efficiency because heating and cooling systems are not employed thus theoretically there is no weather-dependent energy use to be measured. Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [17].

A large number of studies have been conducted to investigate the key factors that can influence thermal comfort. Fanger [18] proposed a ‘static’ model based on data obtained in climatic chambers under steady-state conditions, which indicated that thermal preference between people would not be affected by physiological factors or regions. Later, an ‘adaptive’ model developed by de Dear [19,20] based on data collected from field studies in real buildings, which take into account the responses of occupants to achieve thermal comfort, such as opening windows for ventilation or changing their clothing, has led to a wider range of comfort zone than that for the ‘static’ model. The adaptive model was then adopted by American Society of Heating, Refrigerating and Air Conditioning Engineers' (ASHRAE) Standard 55 [21], in particular for investigating the thermal comfort of a naturally ventilated building, where there are opportunities for the occupants to adjust their thermal environment by, for example, opening the windows or turning on fans, and where the occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions. During the last decade, numerous studies have been conducted on the thermal comfort of naturally ventilated buildings around the world, such as studies from McCartney and Nicol [22] (in Europe), Indraganti [23], Indraganti et al. [24], Indraganti and Rao [25] (in India), Candido et al. [26] (in Brazil), Goto et al. [27] (in Japan), Zhong et al. [28] (in China), and Saman et al. [29], as well as Soebarto and Bennetts [30] (in Australia).

According to the adaptive model, the acceptable indoor operative temperature T_i have a linear relationship with the prevailing mean outdoor temperature [17,19], which can be calculated by: $T_i = 0.31 * T_o + 17.8$, where T_o = Prevailing mean outdoor temperature.

This standard specifies the boundary conditions of a space that provides acceptable thermal environment for 80% or more of the occupants. The upper and lower limits of the indoor operative temperature corresponding with 80% (90%) acceptability are defined by extending the indoor comfort temperature by ±2.5 °C (±3.5 °C) [20]. The prevailing mean outdoor temperature (T_o) is determined based on a simple arithmetic mean of the mean daily outdoor air temperatures of seven days prior to the day in question (T_n), using the exponentially weighted running means as explained in Refs. [31,32] as shown in the following equation: $T_o = 0.34T_1 + 0.23T_2 + 0.16T_3 + 0.11T_4 + 0.08T_5 + 0.05T_6 + 0.03T_7$.

3. Methodology for parametric study

The investigation was based on thermal simulation of a hypothetical base building which is naturally ventilated and has uninsulated rammed earth external walls. Individual as well as combined design parameters are then implemented methodically to find out their impact on the building's indoor thermal comfort.

The simulation program used was *AccuRate* [33], developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). *AccuRate* predicts the thermal behaviour of a building using a frequency response method, the key technique of which is to obtain the frequency response functions and transient response factors from the relationship between a set of inputs (climatic information and thermal properties of building elements) and outputs (the software can output the energy loads for heating and cooling that required to produce thermal comfort, or export the indoor temperatures for houses without air-conditioning) [34]. The software has been validated both empirically and through intermodal comparisons [35–38].

3.1. The “basic model house”

A basic model house was developed as the reference case, which was a single zone house (12 m × 8 m) facing true north as shown in Fig. 1. A simplified single zone house is commonly used for such investigation, such as in studies conducted by Delsante [36], Daniel et al. [37] and Wang et al. [39]. The ceiling of the basic model house consisted of R 3.0 glass fibre batt and 10 mm thick plasterboard, above which there was a pitched roof (with an angle of 30°) consisted of R 1.0 glass fibre batt insulation and 1 mm steel sheet. Ceiling was highly insulated in order to minimize the effect of other parameters (except for the external walls) on the thermal comfort of the model house. Similarly, no internal walls were applied in the basic model as this study aimed at investigating the effect of the main design parameters that relate to the external envelope (which play an important role on the heat exchanges between the inside and outside of a house) on the thermal comfort. Internal walls which are normally constructed with light-weight materials has no significant influence on the overall thermal comfort of the entire house as they mainly affect the heat exchanges between two adjacent zones inside the house rather than heat exchanges between the inside and outside of the house.

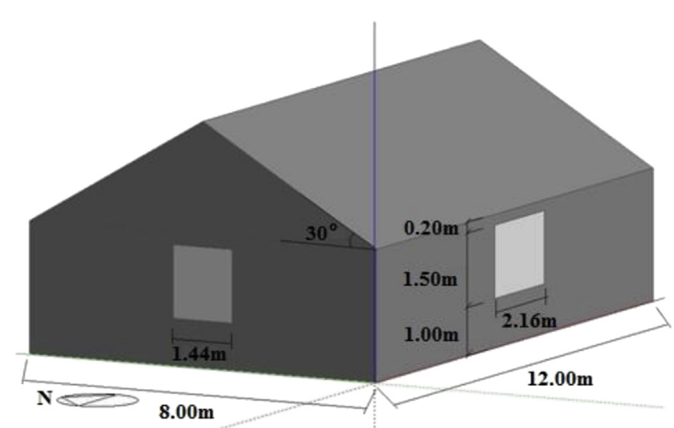

Fig. 1. Basic model house.